Study on the Microstructure and Load Bearing Properties of Granular Material

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***Abstract*—The mechanical properties of granular materials such as loading and deformation resistance are closely related to the microstructure of the material. A FEM simulation work on random diameter size particle system along with the loading process of vertical compression and the transverse shear are carried out in this paper. The contact force chain and the load bearing skeleton in particle system are observed under the compressed and shear load while the results of numerical simulation is verified by a photo-elastic test. The results from numerical simulation and photo-elastic test shows that the force chains grows up gradually until a stable load bearing skeleton formed in loading process. With the load of threshold value reached or bearing direction changed, the load bearing skeleton would go to instability and collapsed rapidly. The results also show stress fluctuation in granular material on macro-scale. The load bearing skeleton in particle system has obvious directivity and if the bearing direction is changed it will quickly lead to the skeleton failure. The fabric tensor is considered to express a bulk stress on granular material. This paper also studies the stability of load bearing skeleton with different friction between particles.**

***Index Terms*—granular material, micro-structure, load bearing direction, force chain, orthotropic**

I. Introduction

Mechanical behavior of granular materials is closely related to its microstructure characteristics. The microstructure characteristics of the particles includes the shape and size of particles and also the particles spatial arrangement. The geometrical properties of individual particles not only has an effect on the spatial arrangement of particles but it is also the main factors that affecting the internal stress and displacement in the Particle system. The spatial arrangement of particles can be constructed by the particle position and contact relationship. The simplest form is the Voronoi graph and Dirichletgraph [1] which are formed by the space of discrete points using boundary line (2D) or edge (3D). The discrete points can be connected to the Delaunay triangulation on the basis of the Voronoi graph. Satake [2] for the two dimensional particle system by the contact of the center point of the particles and the particle gap center point line to build a set of dual graphics system that is the particle graphics system (particle-graph) and the space graphics system (viod-graph), the random distribution of the particle space topological characteristics. Bagi [3] constructs a set of pair graphics system that is the material cell system and space (cell system). Li and Li [4] constructed a set of pair geometry systems based on the particle contact points and formed a complete structure of the contact structure of the particles with the solid phase cell elements and cellular elements. These particles can express the characteristics of particles spatial location but it cannot reflect the mechanical behavior such as load bearing of the Micro-structures.

The load bearing structure of the particle system can be described by the force chain which is produced by the contact force of the particles. We can obverse the force chain mesh in the granular system directly by the photoelasticity test [5], [6] and discrete element numerical simulation [7]. Through the analysis of the experimental observation the stress region of the disordered arrangement of particles has a parabolic boundary which is different from the theory of continuous medium elasticity, and the discrete element simulation results show that the stress is not uniform [8].

It is a feasible method to reveal the mechanism of complex mechanical behavior of the particle system by the means of force chain analysis. The transfer of force chain in the local area is anisotropic and the number of particles in the system will deviate from the mechanical elastic characteristics which shows the strong fluctuation [9], [10]. When the number of particles is large enough the system still shows the elastic characteristics, the friction coefficient of the particles, the disorder degree of the system and the performance of the force chain is isotropic. Many scholars have carried out the research on the physical and mechanical properties of the particle system based on the description of the force chain. Through the study of dynamic effect of the particles in the center of the three-dimensional model, the effect of disorder degree on the mechanical properties of the particles is analyzed and the comparison of the Boussinesq [7] solution with the Silbert [11] solution is made. Some scholars have tried to use the complex network method to study the internal force chain structure of granular material. Andrade and Apollonian [12], Mertensand Arevalo [13], the static topological properties of the force chain are studied. Tordesillas [14] and other will further study the structure evolution of the force chain of dense particle system.

In this paper a numerical simulation and experimental study was done on the fine structure of the random

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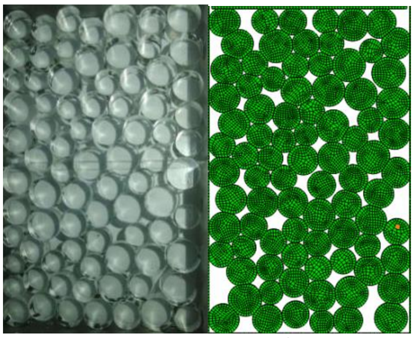
particle system in the vertical compression and horizontal shear. Firstly the two-dimensional circular particle size distribution was calculated. The experimental results were made by using the method of laser cutting. The contact, separation of fine particles and the evolution of the force were observed by using the method of optical test. In the end the stability and evolution characteristics of the micro structure of the corresponding materials were analyzed by the simulation of different circular particle size.

The purpose of this paper is to study the characteristics of the fine particles in the particle system when the loading is observed. So the test load is slow but the dynamic effect can be neglected. At the same time in the explicit dynamic finite element calculation the influence of the distribution of the contact force is very small.

II. Design Methodologies

A. Numerical Simulation of Granular Material through Compression and Shear Loading

In the photoelasticity test model and finite element model the granular material element is designed as 130x80mm2 (LxW) area and 84 number of particles are distributed randomly in the region (Fig. 1). Through the physical model test and the numerical finite element simulation the loading process of vertical compression and horizontal shear is subjected.



(a) The photoelasticity test model (b) The finite element numerical model

Figure 1. Random particle material element model

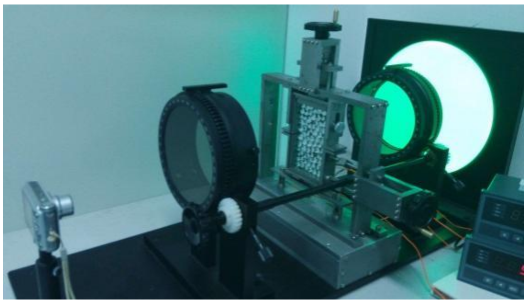


Figure 2. The photoelasticity test loading device

B. Micro Particle Photoelasticity Test

The image of the particles is observed by using the particle dielectric material. The granular medium material is composed of an optical device and a bidirectional loading device, as shown in Fig. 2. With the loading of the load the sensor can record the vertical reaction force of the material transfer in the loading process.

By using laser cutting technology the disc thickness is 10mm and the diameter of the disc is placed in the same position with the finite element numerical model. The loading process is that first slowly rotating the vertical loading handle for vertical compression to reach the predetermined position and then slowly rotating the horizontal loading handle for shear loading. The change of the force chain of the disc is loaded at the same time while the vertical and horizontal reaction force is recorded by the force sensor in the test device and the finite element analysis is carried out. The experimental results are compared with the numerical simulation results.

The ratio of the particle to the total area of the disc and the area of the particle system is 0.806.The experimental images were taken to observe the change of the particle system in the process of loading and the results were as shown in Fig. 4-Fig. 6.

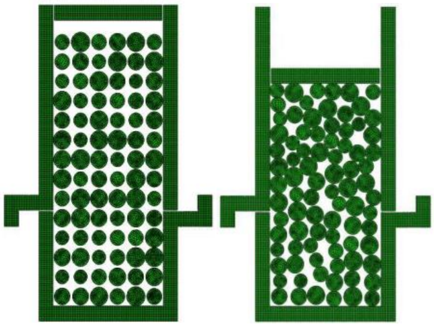


Figure 3. Finite element loading model

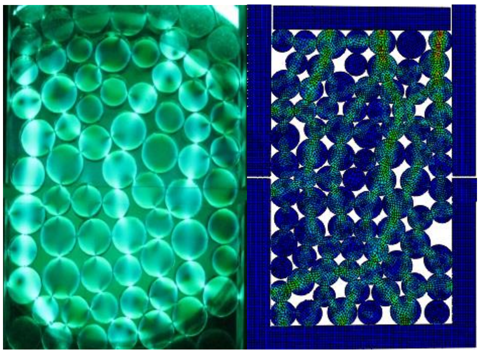


Figure 4. Shear displacement s=0mm

C. Numerical Simulation by FEM

Finite element model was established according to the design element of the granular material. As shown in Fig. 3 the model is applied to the vertical compression by moving the roof of the particle model and the shear load is applied to the particle model through horizontal moving the upper frame. The structure load particle system was used in the model and the particle volume ratio was 0.806. The load of the load cell is made of steel and the material of the particle is made of plexiglass while the vertical loading process are simulated by explicit finite element method. For each particle the particle boundary is defined as the contact boundary with the friction coefficient of 0.9 and the dynamic process of the particle contact and separation process is simulated by the vertical compression and horizontal shear.

III. Results and Discussions

Through the experimental and finite element numerical simulation of the particle system of a set of random particle size distribution the stress distribution of the elastic stress and the force chain diagram are obtained respectively. The results of the distribution of force chains are shown in Fig. 4-Fig. 6.

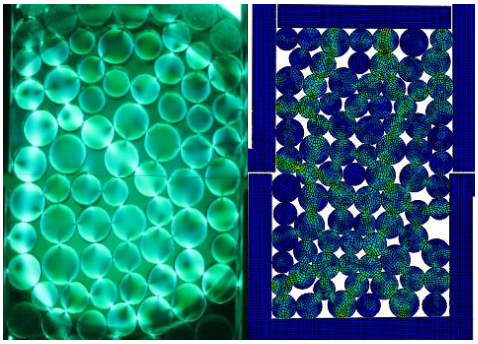


Figure 5. Shear displacement s=5mm

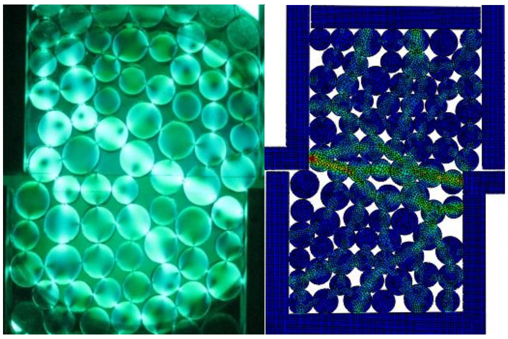


Figure 6. Shear displacement s=17mm

From the experimental and numerical simulation results of the stress distribution of the fine particles can be seen. In the loading process the particle configuration of the random particle space arrangement is roughly the same as that of the numerical simulation. This shows that the distribution of the force chain is closely related to the arrangement of particles and the particle configuration is the direct cause of the distribution of the force chain. The results show that the finite element model and the algorithm can accurately reflect the load characteristics of real particles and can be carried out by numerical method to analyze the structure of the particles.

At the same time it can be seen from the comparative results that although the location of the front loading and the numerical model is completely consistent but the particle moving position will produce small differences which also shows that the particle system space configuration evolution rate is often random and the characteristics of the particle structure should be based on statistical analysis method.

A. *Force Chain Characteristics of the Particle System*

Iwashita thought that the disappearance of the force chain has two ways one is through the unloading of external forces applied on the particles the other is through the force chain buckling deformation [15].

The loading process is as follows: Firstly the vertical compression is carried out and the bearing capacity of the granular material is formed then the horizontal shear loading is carried out. Through the observation of the experiment the vertical loading process of the random particle system is gradually formed and the vertical direction of the force chain is gradually cleared while the transmission capacity is enhanced and the bearing structure is gradually formed. Fig. 7 is the shear test process observed that the force chain collapse when the boundary vertical reaction reaches from 241.5N to 32.1N meanwhile the force chain disappeared and gradually reconstructed. With the increase of horizontal shear displacement the horizontal distribution of the force chain structure is gradually formed.

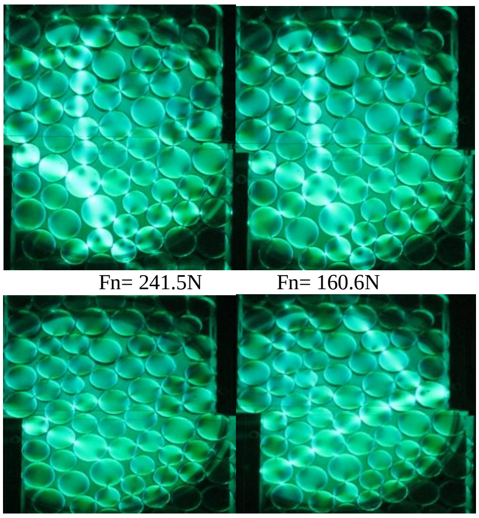


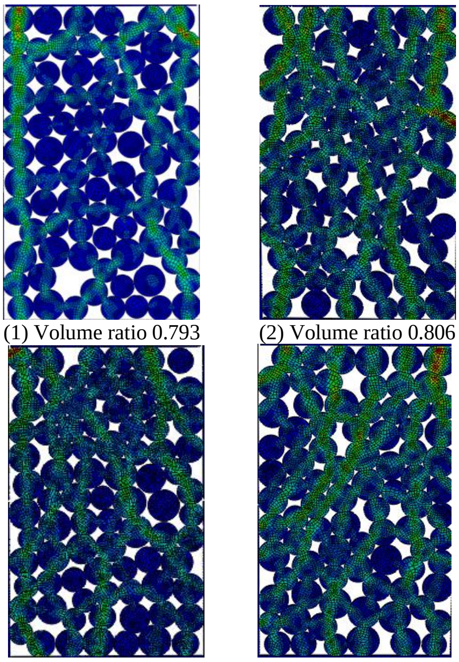
Figure 7. Force chain collapse while shear loading process

In the process of particle system the formation, failure and reconstruction of the load process show that the particle size of the bearing structure has a significant direction and the change of the bearing direction will cause the instability of the structure. Therefore the expression of mechanical properties of granular materials should be considered in the direction of the microstructure and the expression of stress and strain can be established based on the structure tensor.

B. *Influences of Volume Ratio and Friction Coefficient in Force Chain*

The finite element numerical method is used to simulate the generation of different random distribution of granular materials and the moving top boundary is applied to vertical loads. Using the same material model and load application method 4 kinds of random particle operating conditions are selected to carry out comparative analysis (Fig. 8). The distribution of the force chain was found to be completely different from the different particle distribution.

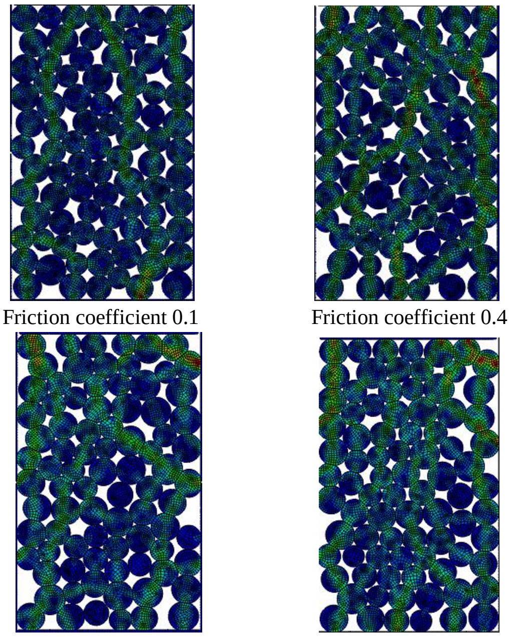
The same material model and load application method were used to select a specific random particle initial distribution (0.838) boundary of different friction coefficient, the vertical load and the observation of the distribution of the force (Fig. 9). On the results the distribution of the force chain is not significantly similar.



(1) Volume ratio 0.793 (2) Volume ratio 0.806

(3) Volume ratio 0.821 (4) Volume ratio 0.838

Figure 8. Distribution of force chains of different random particles (Friction coefficient is 0.6)



Friction coefficient 0.1 Friction coefficient 0.4

Friction coefficient 0.7 Friction coefficient 0.9

Figure 9. Force distribution of particles with different friction coefficient (Volume ratio 0.838).

The results show that under the same load the particle size distribution of the particles is directly influenced by the particle size distribution, the particle friction coefficient and other parameters have a significant effect on the spatial configuration of the particle system. Therefore for the random distribution of particle the load bearing chain is difficult to characterize the load model of granular material in a random pattern.

C. Bearing Capacity of the Particle System

In the photoelasticity test model and the finite element method simulation each group of randomly generated 84 particles on the vertical compression are set in the box of 130 x 80mm2. Simulation calculation of the maximum vertical reaction force of the loading process and the bearing capacity of the particle system is analyzed. The calculation results of the various working conditions are summarized as shown in Fig. 10.

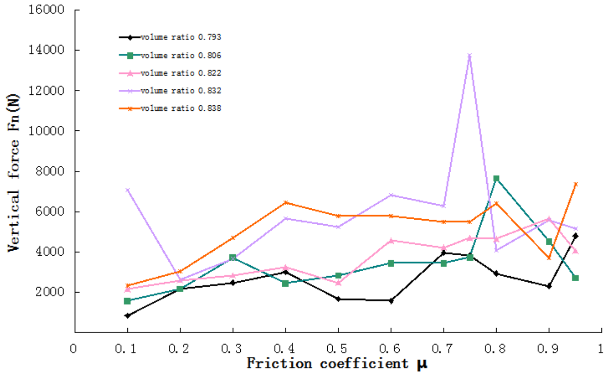


Figure 10. Maximum vertical reaction force of a particle material

From the results, it can be seen that a few examples are not following the physical law that is larger the compression volume of the homogeneous material is larger the force. Such as maximum volume ratio (0.828), the particle friction coefficient is 0.1, 0.6, 0.7, 0.8, 0.9, 0.75, etc. This phenomenon shows that the mechanical properties of granular materials are not fully compliant with the general mean of elastic constitutive properties. Since the friction coefficient of particles increases then the reaction force is also increased but the law is not very significant. This phenomenon shows that the friction coefficient of the material has a certain effect on the mechanical properties but also shows that the mechanical properties of the particles are complex.

It can be seen from the analysis that the randomness of the random particle system is an important reason for the complex physical and mechanical properties and the particle configuration is not only influenced by the particle shape of the material but also with the external load. To carry out the research on the mechanical properties of granular materials we need to carry out the work on the basis of the detailed understanding of the micro structure characteristics of granular materials.

IV. Conclusion

In this paper the research on the micro structure and load bearing characteristics of the granular medium material model is carried out by using the photoelasticity test and the finite element numerical simulation method. By establishing the random particle system model the analysis is characterized by vertical compression load and horizontal shear load and the characteristics of the micro structure of the material are analyzed by comparing the evolution law and the mechanical property of the granular material. Through this research we can get the following basic conclusions:

1) In the process of loading the granular material it is usually in the form of gradual change to form a stable bearing structure and the instability of the structure forms a sudden change which is manifested as the fluctuation of material stress.
2) The structural characteristics of the particles with the change of the bearing capacity of the particles are significant in the direction of the particles and the structural characteristics of the structure can be described by the structure tensor.
3) The mechanical behavior of the granular material is closely related to the micro structure which is influenced by the particle size and the friction coefficient of the material. The randomness of the fine view configuration is an important reason for the complex physical and mechanical properties of granular materials.

The experimental and numerical analysis of this paper can be used as the basis for the study of the mechanical properties of granular materials in the future.

The further continuation of study in future should be established on an orthotropic constitutive model with the fabric tensor for granular material.

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